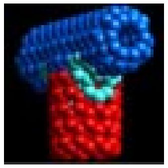
Carbon Nanotube based Nanotechnology



M. Meyyappan
NASA Ames Research Center
Moffett Field, CA 94035
email: meyya@orbit.arc.nasa.gov

web: http://www.ipt.arc.nasa.gov

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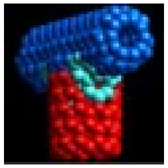
Acknowledgement



Carbon Nanotubes (Experiments)

Alan Cassell
Bin Chen
Lance Delzeit
Wendy Fan
Jie Han
Bishun Khare
Jessica Koehne
Jun Li
Cattien Nguyen
Ramsey Stevens

Protein Nanotubes

Jonathan Trent
Andrew McMillan

Nanotechnology in Genetics

Jim Kaysen
David Loftus
Victor Stolc

Computational Nanotechnology

M. Anantram
Charlie Bauschlicher
Chris Dateo
Tahir Gokcen
Richard Jaffe
Natalio Mingo
Alessandra Ricca
Deepak Srivastava
Steve Walch
Toshi Yamada
Liu Yang

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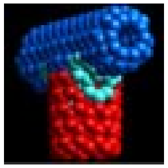
Ames Nanotechnology Research Focus



Nanotubes

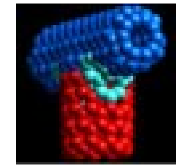
- Controlled, patterned growth of CNT
- Large scale production of CNT
- CNT-based biosensor for cancer diagnostics
- Functionalization of nanotubes
- AFM study of Mars dust
- AFM study of Mars meteorite
- CNT-based sensors for astrobiology
- Hydrogen storage in nanotubes
- Protein nanotubes: growth and applications
- Reactor/Process Modeling of CNT growth
- Computational investigation of electronic, mechanical and other properties of CNT
- Transport in CNT, Nanoelectronics
- BN nanotubes, structure and properties
- Design of CNT-based mechanical components

• Chemical Storage of Data
• Atomic Chain Electronics
• Bacteriorhodapsin based holographic data storage

Computational Electronics, Computational Optoelectronics

- Development of multidimensional quantum simulators to design ultrasmall semiconductor devices
- Development of semiclassical methods with quantum correction terms
- Investigation of device technologies suitable for petaflop computers
- Modeling of optoelectronics devices, VCSEL, THz modulation
- Optical interconnect modeling

What is Nanotechnology?



Nanotechnology is the creation of functional materials, devices and systems through control of matter on the nanometer length scale and exploitation of novel phenomena and properties (physical, chemical, biological) at that length scale

"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."

-Neal Lane
Assistant to the President for Science
And Technology

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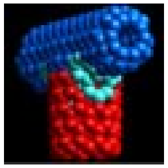
Examples of Nanostructures

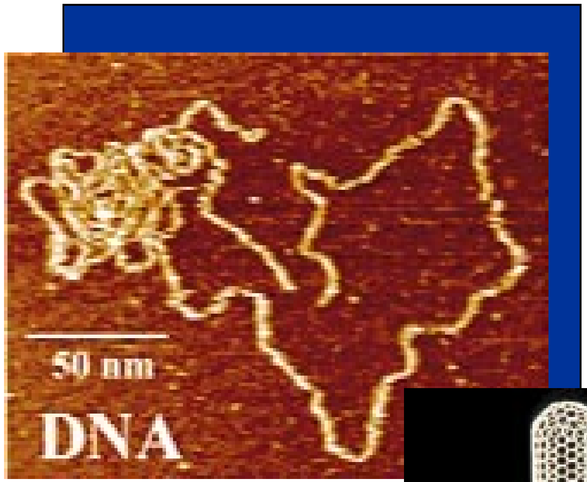


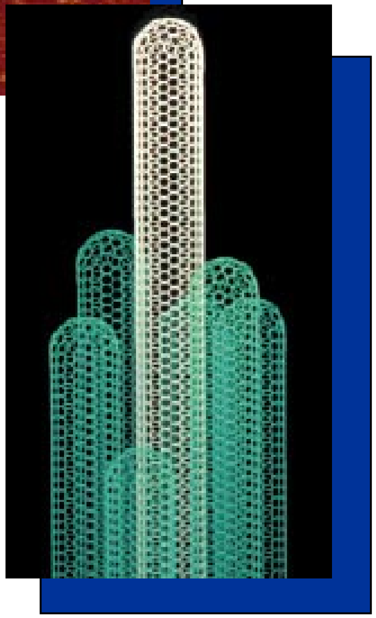
- New behavior at nanoscale is not necessarily predictable from what we know at macroscales.

- Not just size reduction but phenomena intrinsic to nanoscale
  - Size confinement
  - Dominance of interfacial phenomena
  - Quantum mechanics

- Examples
  - Carbon Nanotubes
  - Thin Films of atomic dimensions
  - Proteins, DNA
  - Single electron transistors

AFM Image of DNA





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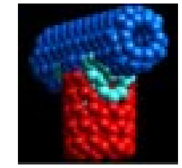
Why Nanotechnology at NASA?



- Advanced miniaturization, a key thrust area to enable new science and exploration missions
  - Ultrasmall sensors, power sources, communication, navigation, and propulsion systems with very low mass, volume and power consumption are needed

- Revolutions in electronics and computing will allow reconfigurable, autonomous, “thinking” spacecraft

- Nanotechnology presents a whole new spectrum of opportunities to build device components and systems for entirely new space architectures
  - Networks of ultrasmall probes on planetary surfaces
  - Micro-rovers that drive, hop, fly, and burrow
  - Collection of microspacecraft making a variety of measurements

- In vivo and noninvasive astronaut health diagnosis and prognosis, in vivo therapy

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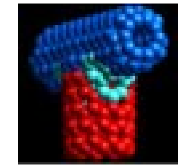
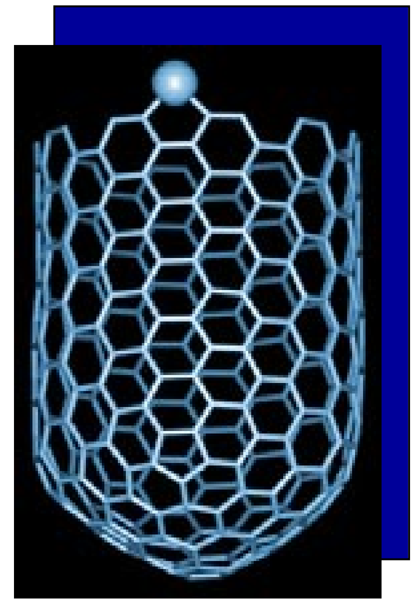
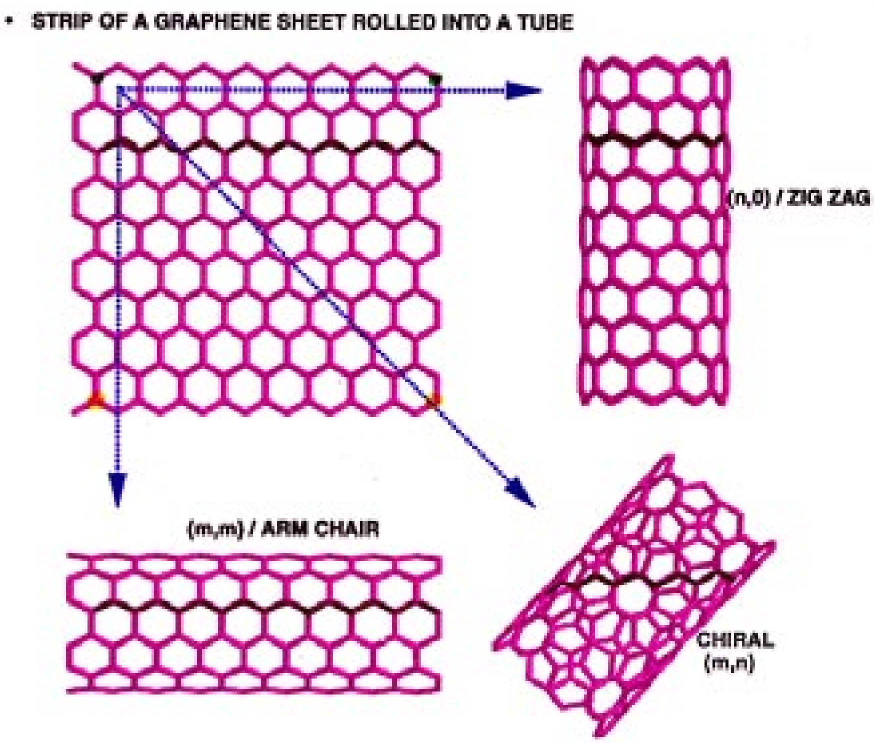
Carbon Nanotube





CNT is a tubular form of carbon with diameter as small as 1 nm.
Length: few nm to microns.

CNT is configurationally equivalent to a two dimensional graphene sheet rolled into a tube.



CNT exhibits extraordinary mechanical properties: Young's modulus over 1 Tera Pascal, as stiff as diamond, and tensile strength ~ 200 GPa.

CNT can be metallic or semiconducting, depending on chirality.

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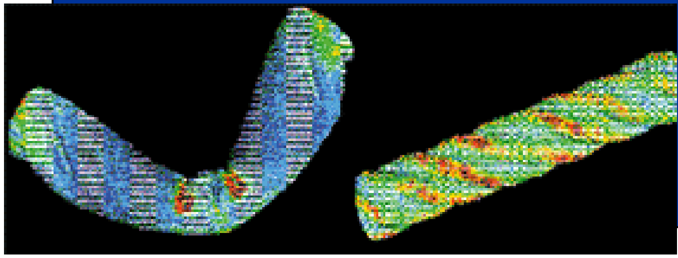
CNT Properties

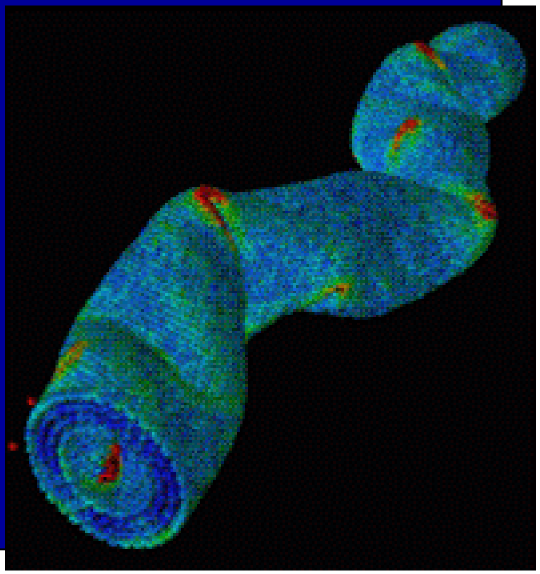
- The strongest and most flexible molecular material because of C-C covalent bonding and seamless hexagonal network architecture

- Young's modulus of over 1 TPa vs 70 GPa for Aluminum, 700 GPA for C-fiber
  - strength to weight ratio 500 time > for Al; similar improvements over steel and titanium; one order of magnitude improvement over graphite/epoxy

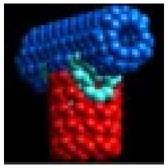
- Maximum strain 10-30% much higher than any material

- Thermal conductivity ~ 3000 W/mK in the axial direction with small values in the radial direction

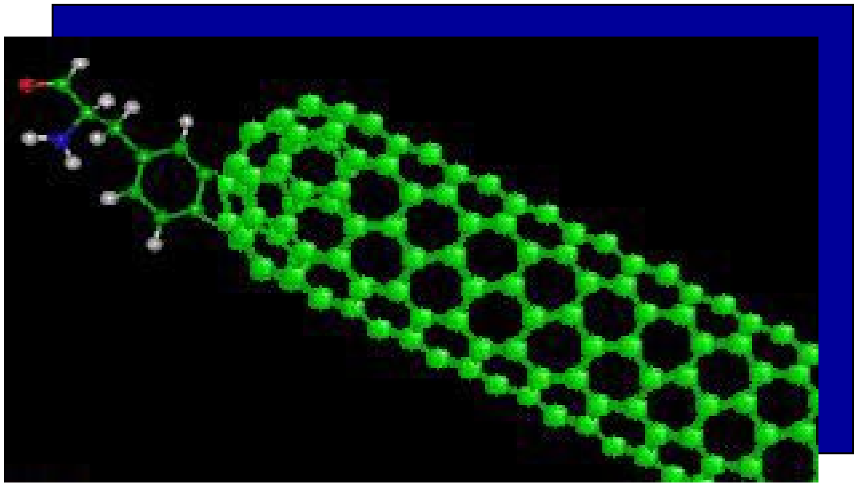


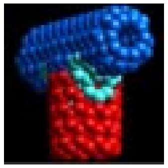


CNT Properties (cont.)



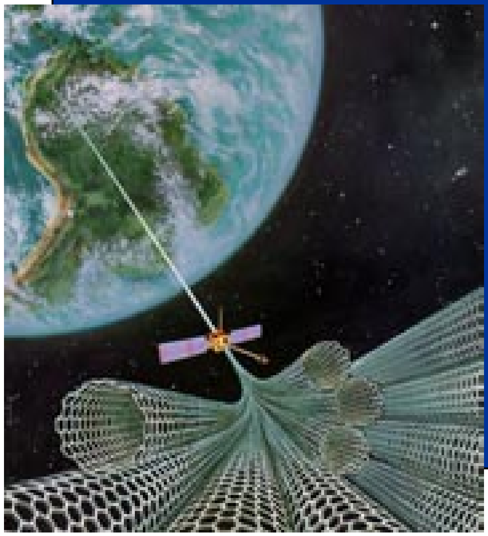
- Electrical conductivity six orders of magnitude higher than copper
- Can be metallic or semiconducting depending on chirality
    - ‘tunable’ bandgap
    - electronic properties can be tailored through application of external magnetic field, application of mechanical deformation…
- Very high current carrying capacity
- Excellent field emitter; high aspect ratio and small tip radius of curvature are ideal for field emission
- Can be functionalized





CNT Applications: Structural, Mechanical

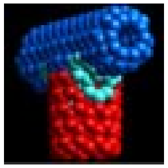
- High strength composites
- Cables, tethers, beams
- Multifunctional materials
- Functionalize and use as polymer back bone
  - plastics with enhanced properties like “blow molded steel”
- Heat exchangers, radiators, thermal barriers, cryotanks
- Radiation shielding
- Filter membranes, supports
- Body armor, space suits



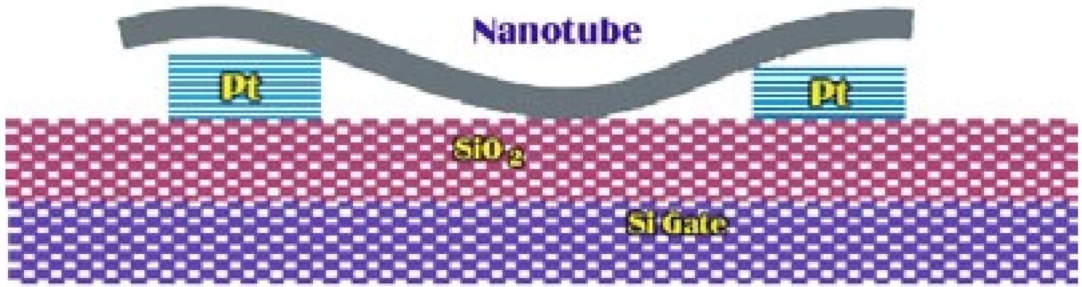
Challenges

- Control of properties, characterization
- Dispersion of CNT homogeneously in host materials
- Large scale production
- Application development

CNT Applications: Electronics



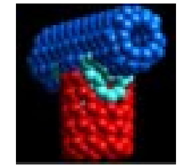
- CNT quantum wire interconnects
- Diodes and transistors for computing
- Capacitors
- Data Storage
- Field emitters for instrumentation
- Flat panel displays
- THz oscillators



Challenges

- Control of diameter, chirality
- Doping, contacts
- Novel architectures (not CMOS based!)
- Development of inexpensive manufacturing processes

CNT Applications: Sensors, NEMS, Bio



- CNT based microscopy: AFM, STM…
- Nanotube sensors: force, pressure, chemical…
- Biosensors for Astrobiology
- Molecular gears, motors, actuators
- Batteries, Fuel Cells: H_2, Li storage
- Nanoscale reactors, ion channels
- Biomedical
  - in vivo real time crew health monitoring
  - Lab on a chip
  - Drug delivery
  - DNA sequencing
  - Artificial muscles, bone replacement, bionic eye, ear...

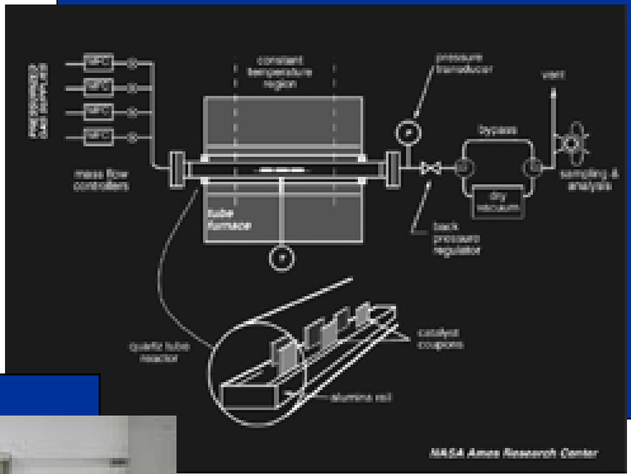
Challenges

- Controlled growth
- Functionalization with probe molecules, robustness
- Integration, signal processing
- Fabrication techniques

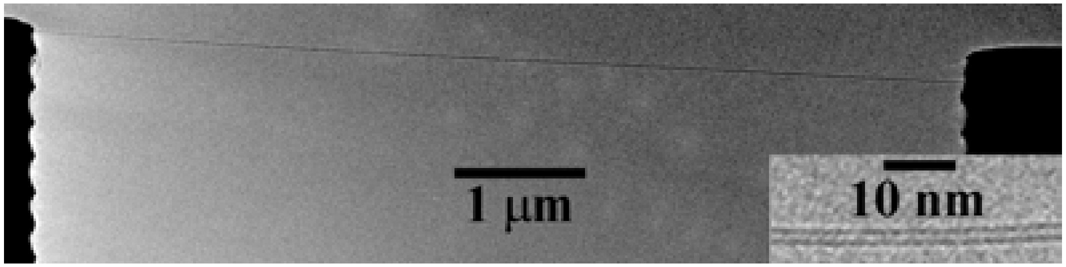
CNT Synthesis

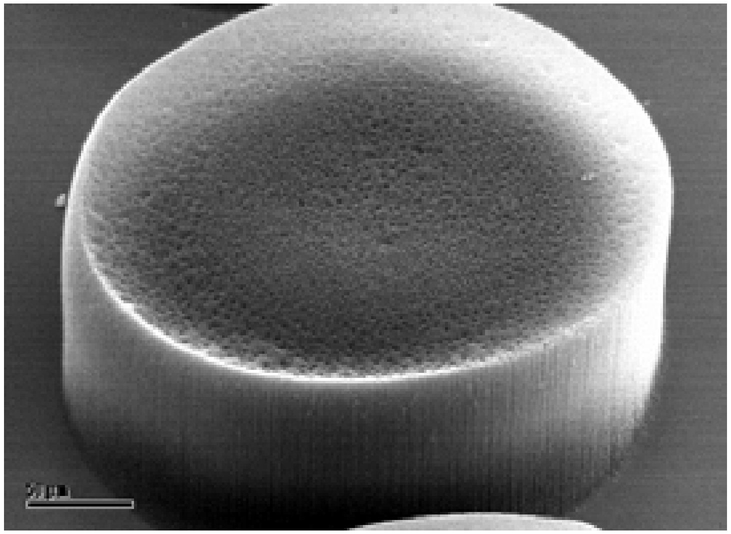
- CNT has been grown by laser ablation (pioneering at Rice) and carbon arc process (NEC, Japan) - early 90s.
  - SWNT, high purity, purification methods

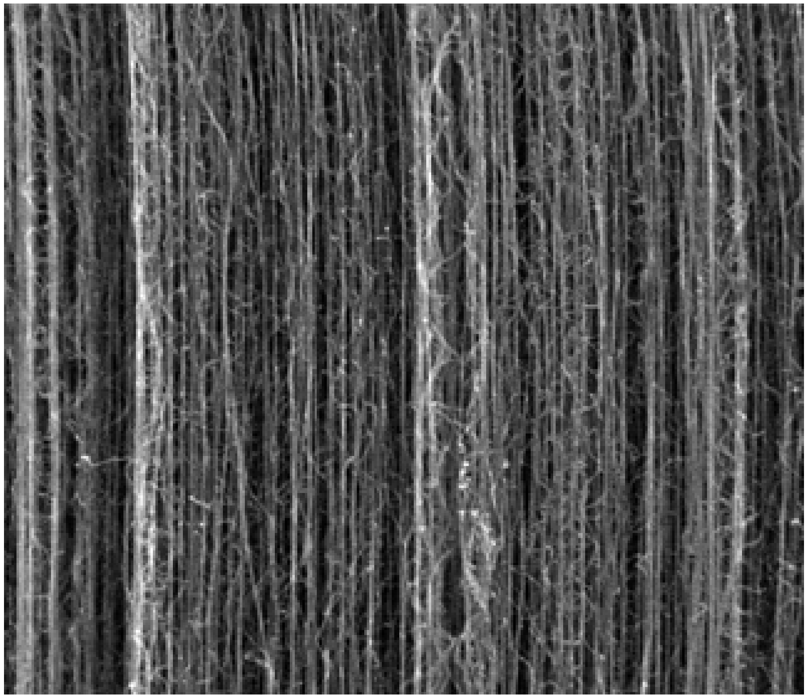
- CVD is ideal for patterned growth (electronics, sensor applications)
  - Well known technique from microelectronics
  - Hydrocarbon feedstock
  - Growth needs catalyst (transition metal)
  - Multiwall tubes at 500-800° deg. C.
  - Numerous parameters influence CNT growth

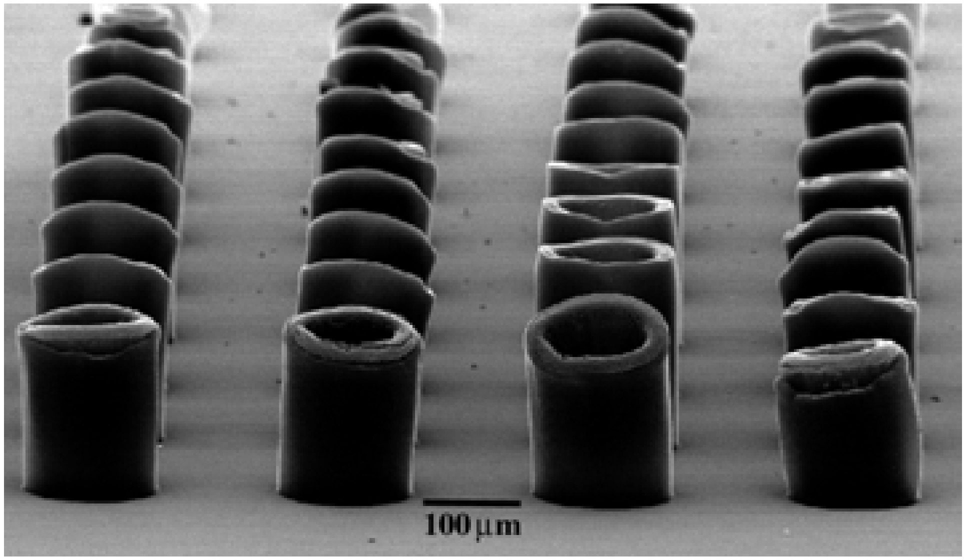


Carbon Nanotubes at Ames

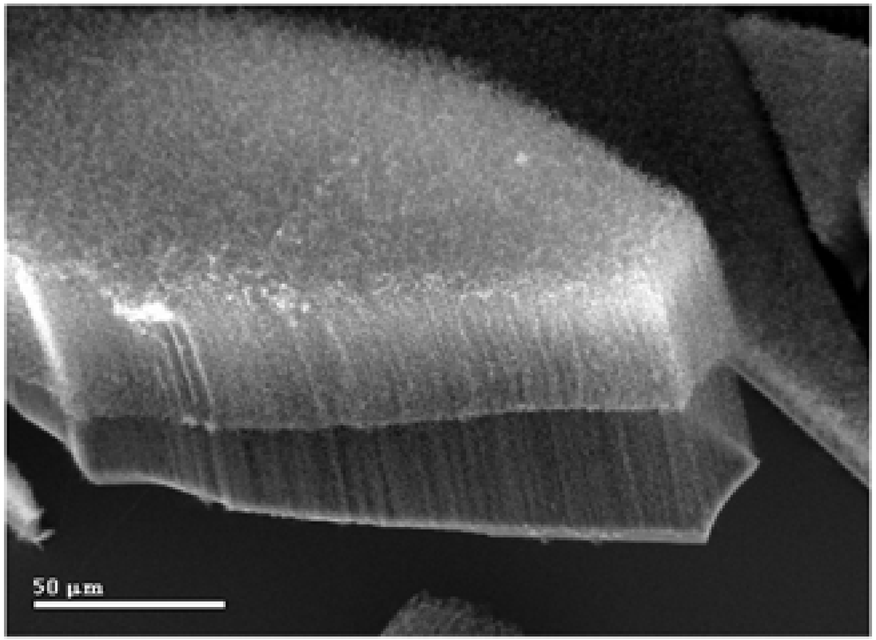


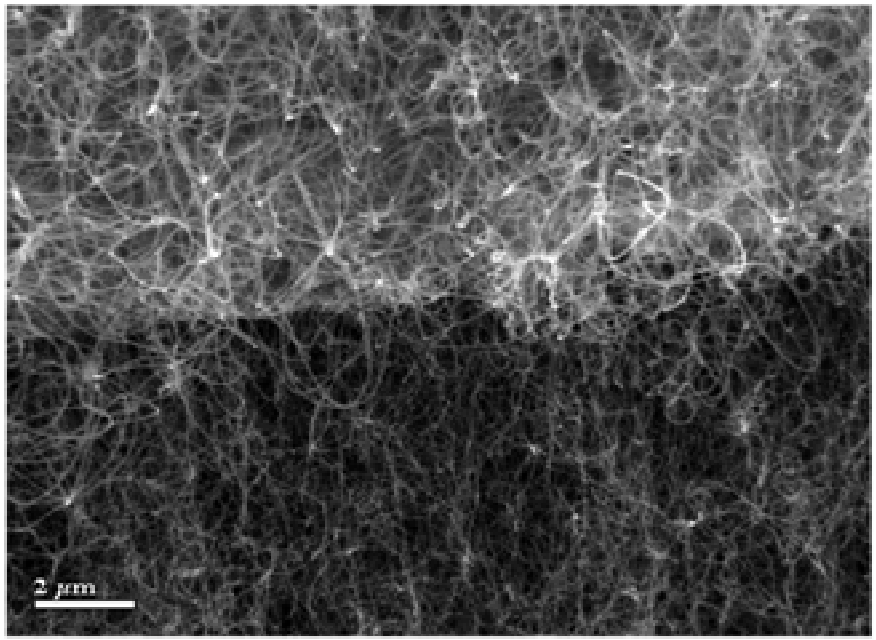




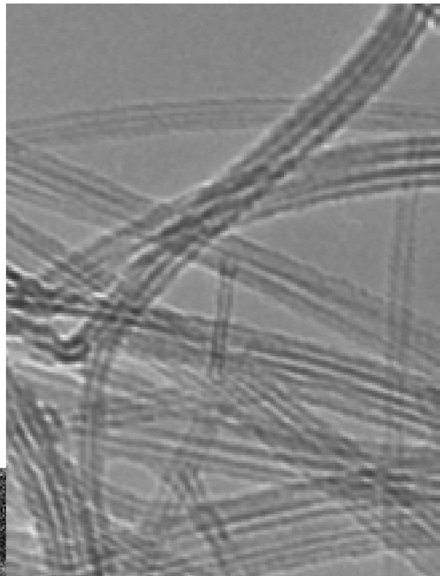


Multilayer Nanotube Growth by CVD

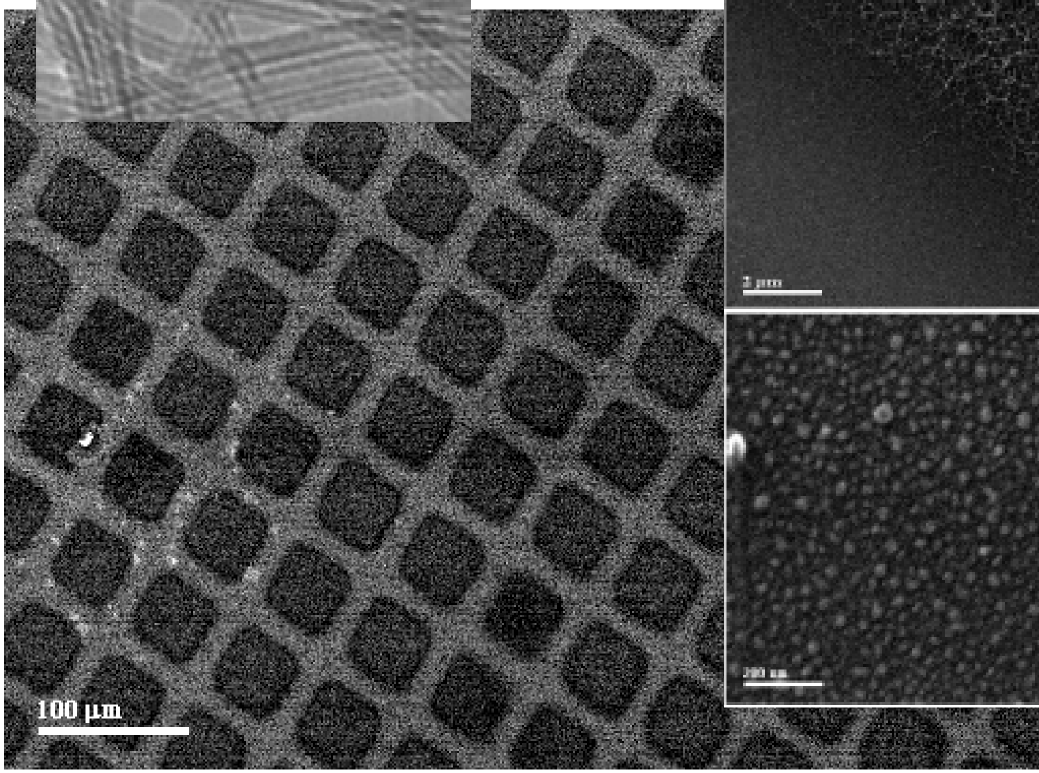


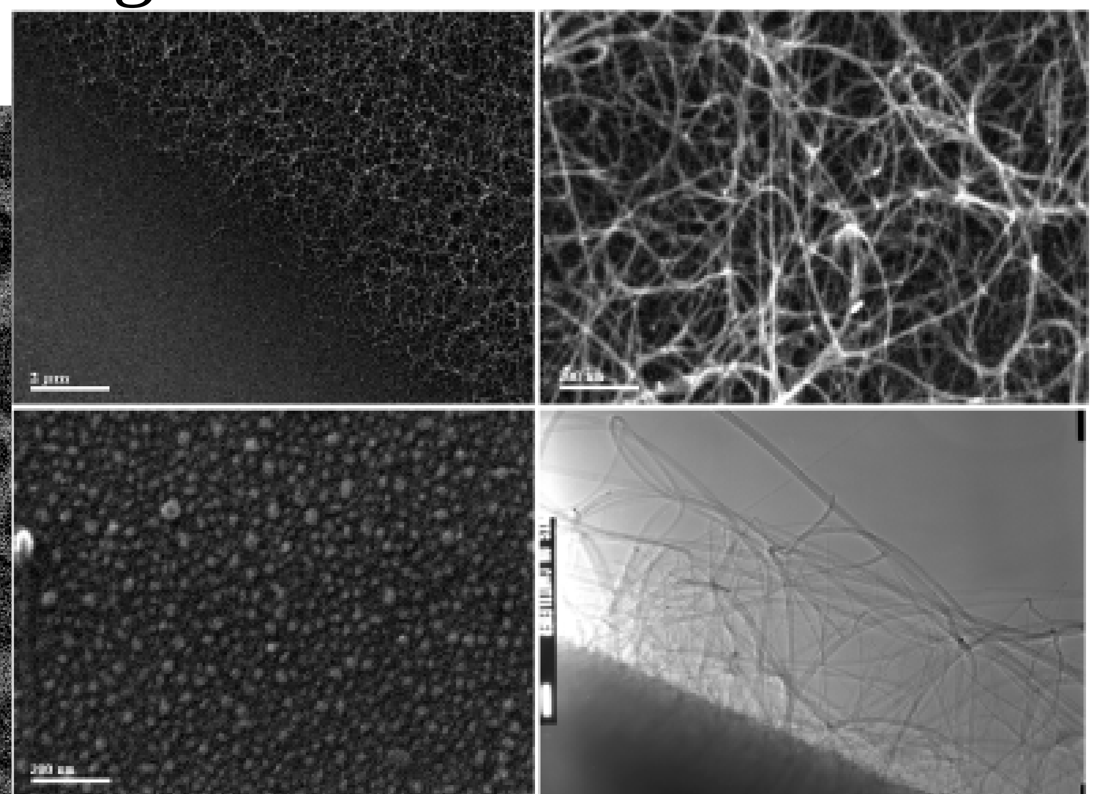


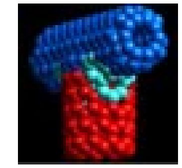
Demonstration of Masking SWNTs



- Surface masked by a 400 mesh TEM grid



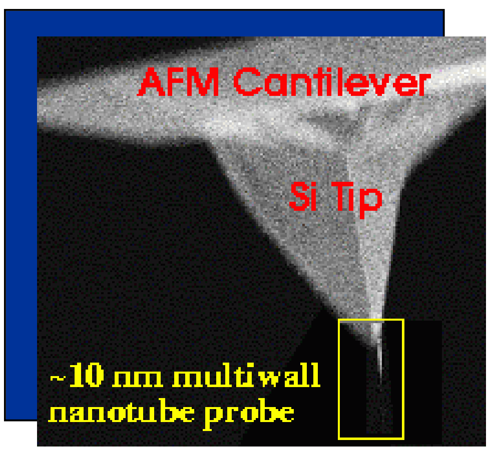




CNT in Microscopy

Atomic Force Microscopy is a powerful technique for imaging, nanomanipulation, as platform for sensor work, nanolithography...

Conventional silicon or tungsten tips wear out quickly. CNT tip is robust, offers amazing resolution.

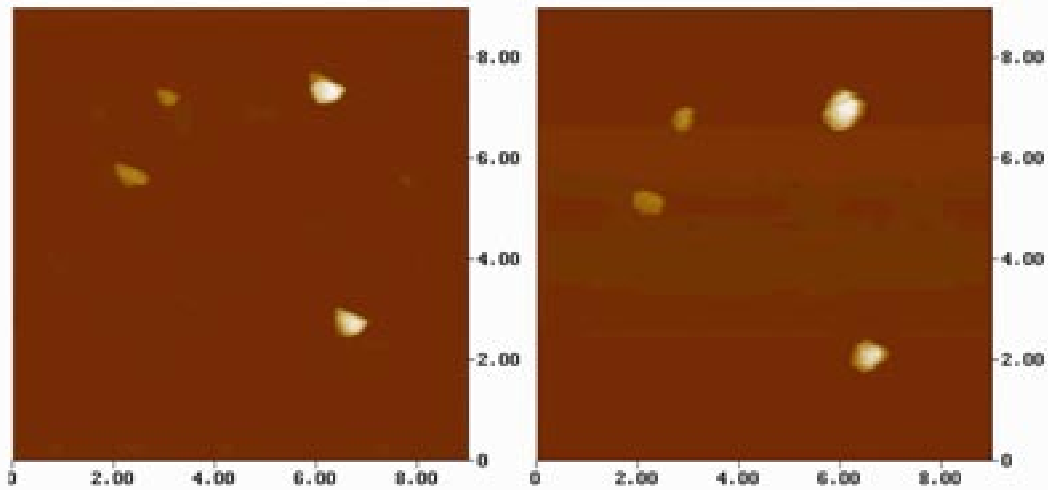


Simulated Mars dust

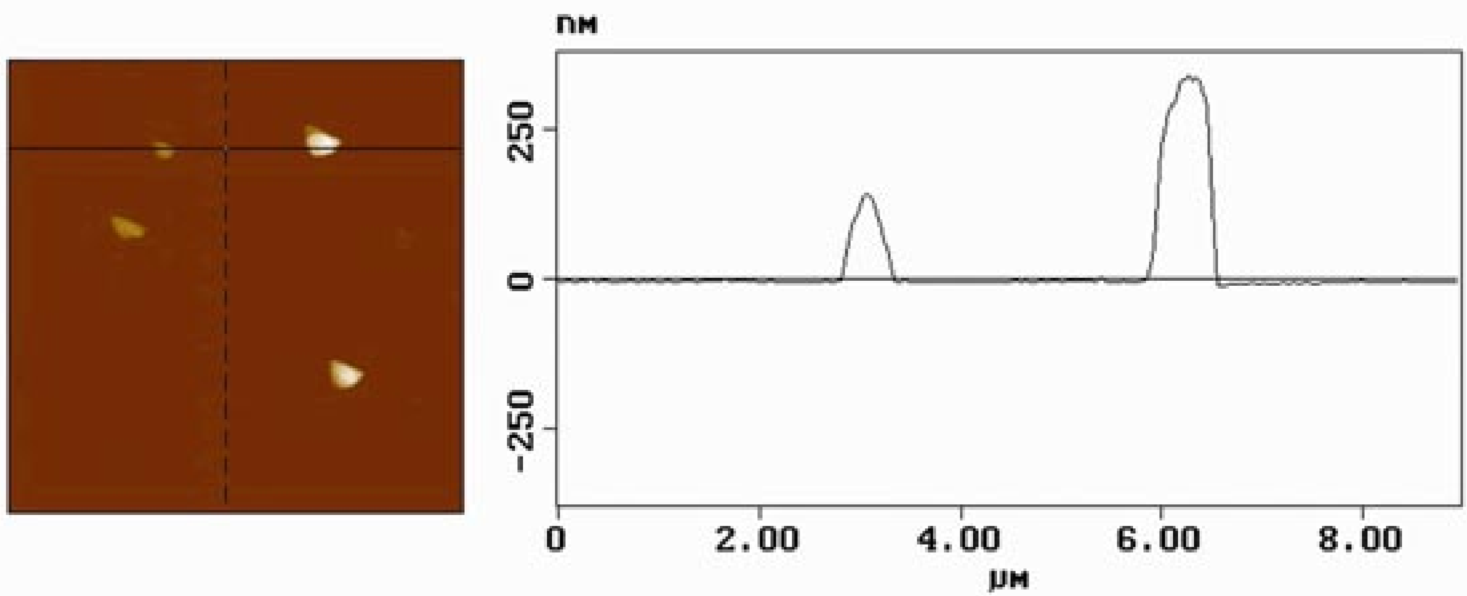
H. Dai

NASA Ames Research Center
Ramsey Stevens, Lance Delzeit, Cattien Nguyen

Tapping mode AFM images of simulated Mars dust on mica using different tips



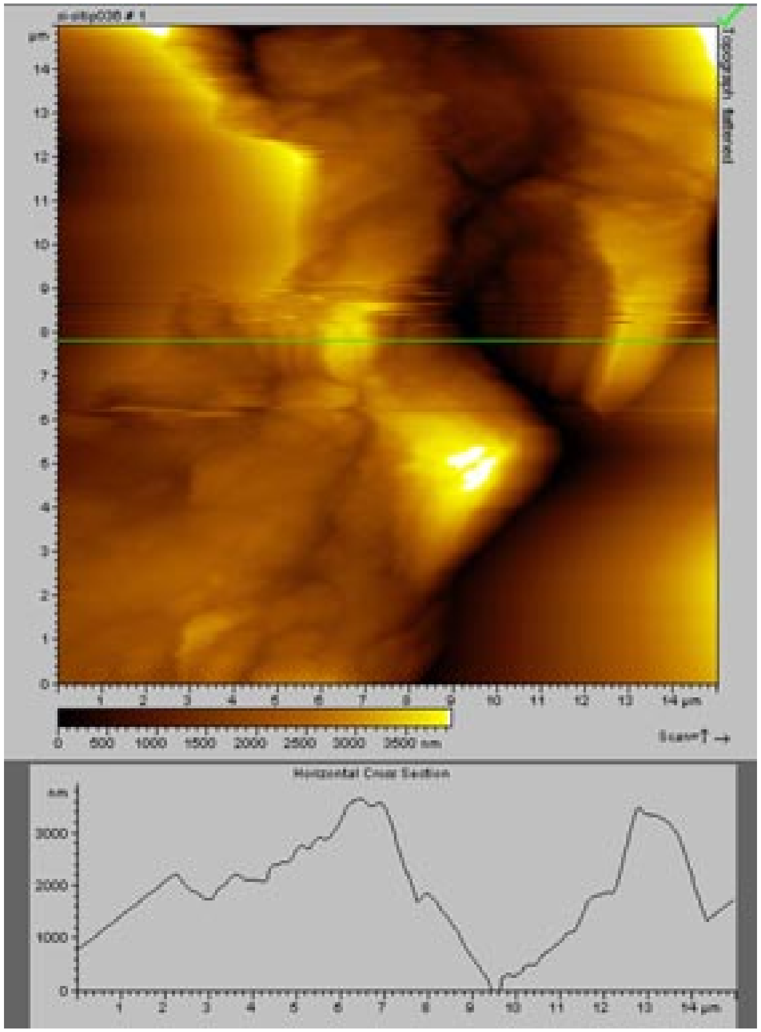
Mars dust imaged with standard silicon tip (left) and a single wall carbon nanotube tip (right). The nanotube tip was reported to be 50-70 nm long and 2-3 nm diameter. original images: simars4.017(left) and tmars4.014



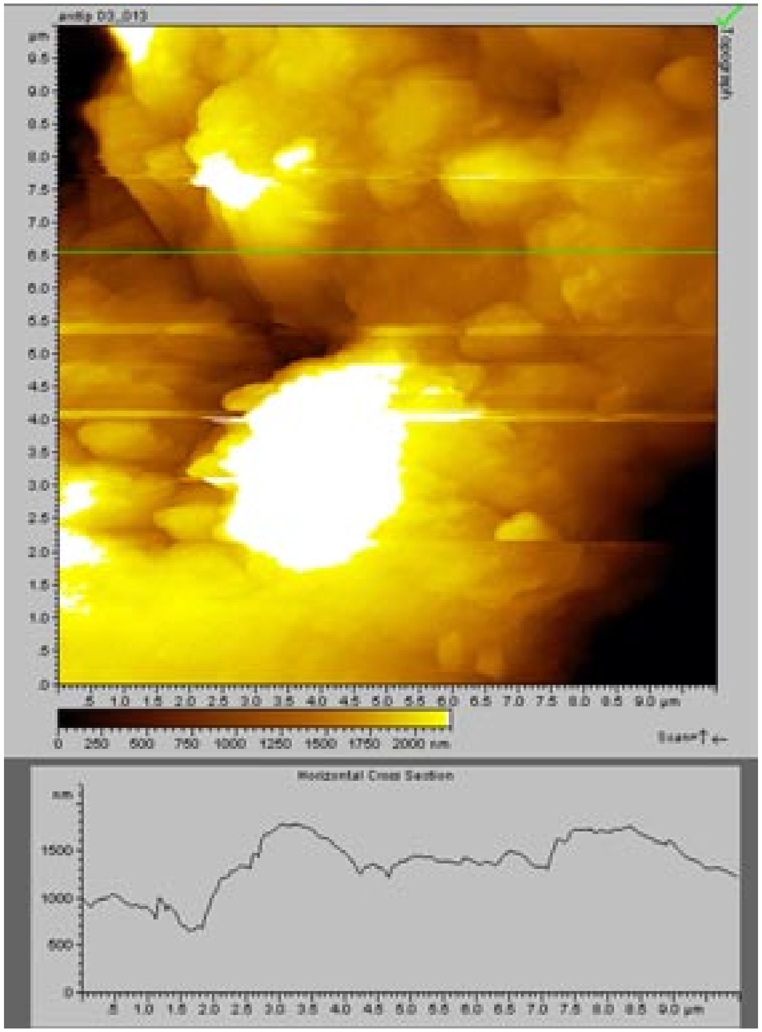
Above: Cross section of simulated mars dust particle imaged with a silicon tip

AFM Images of Simulated Mars Dust

Silicon Tip



CNT Tip



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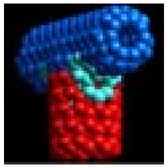
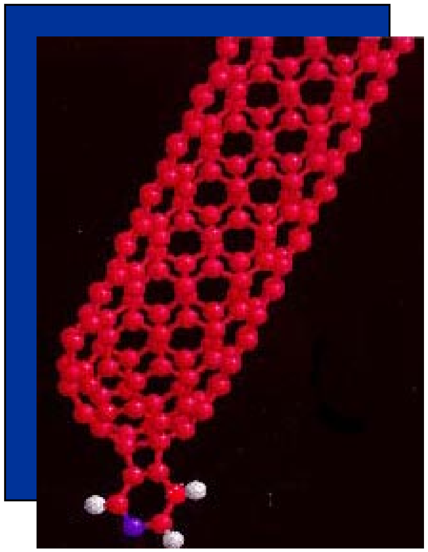
CNT Based Biosensors

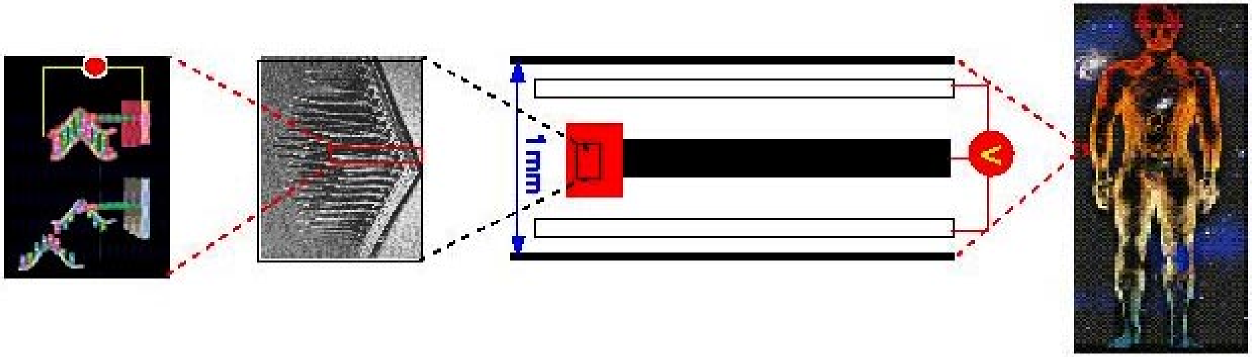


- Our interest is to develop sensors for astrobiology to study origins of life. CNT, though inert, can be functionalized at the tip with a probe molecule. Current study uses AFM as an experimental platform.



- The technology is also being used in collaboration with NCI to develop sensors for cancer diagnostics
  - Identified probe molecule that will serve as signature of leukemia cells, to be attached to CNT
  - Current flow due to hybridization will be through CNT electrode to an IC chip.
  - Prototype biosensors catheter development

- **High specificity**
- **Direct, fast response**
- **High sensitivity**
- **Single molecule and cell signal capture and detection**



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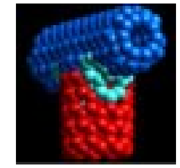
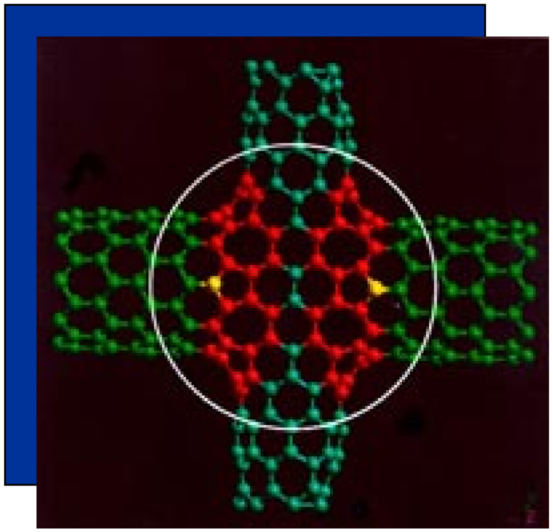
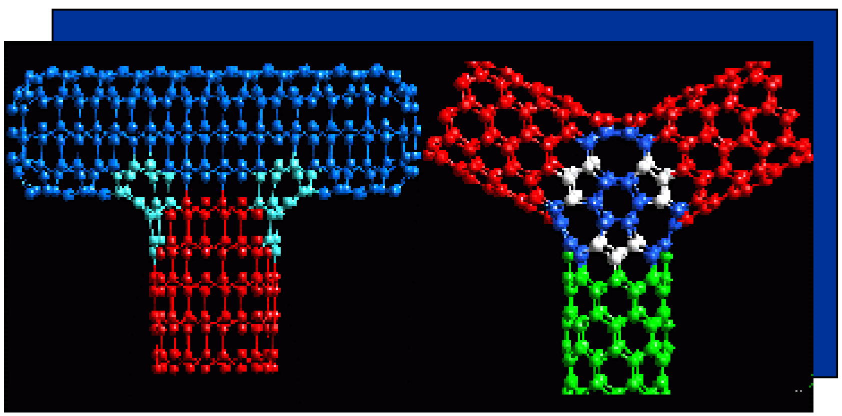
Computational Nanotechnology



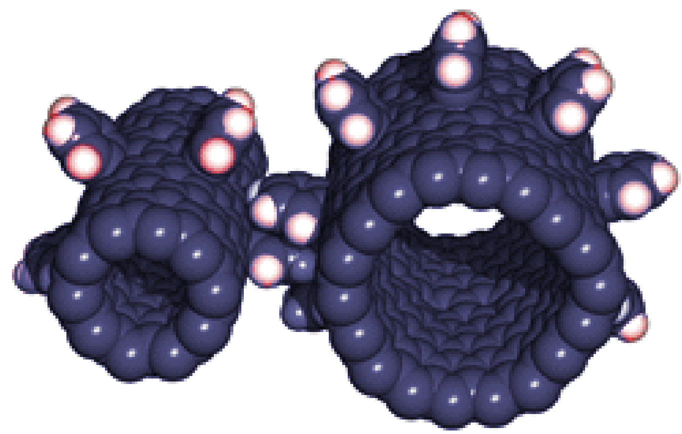


CNT Molecular Network

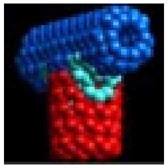
- Large scale computer simulations based on ab initio methods enable understanding nanotube characteristics and serve as design tool
  - Evaluation of mechanical properties
  - Evaluation of electronic properties
  - Electron transport in CNT devices
  - Functionalization of the nanotubes
  - Design of electrical and mechanical devices
  - Evaluation of storage potential (H_2, Li)



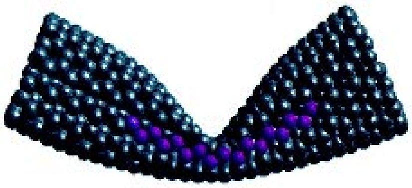
CNT “T” and “Y” Junctions



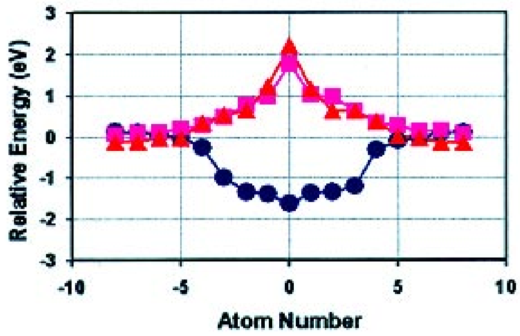
Computational Nanotechnology

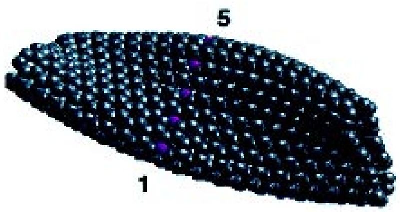


- Predictions of enhanced chemical reactivity in regions of local conformational strains: Kinky Chemistry

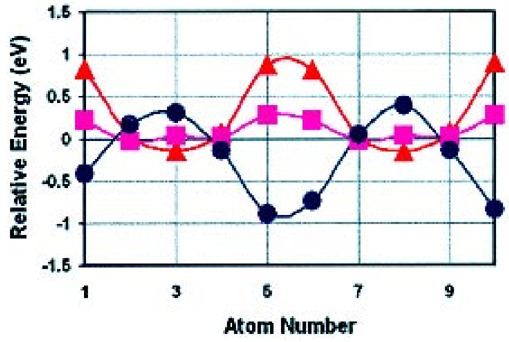


Kink on a bent tubule



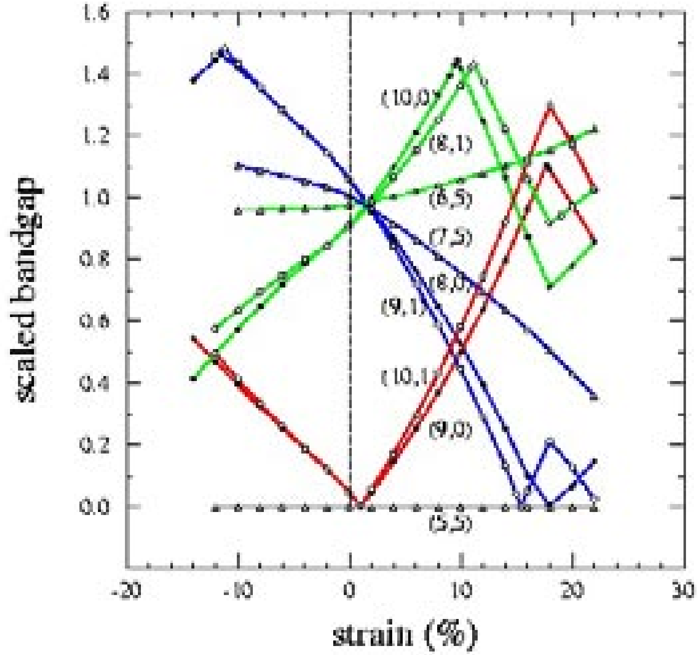


Ridge on a twisted tubule



Binding Energy
Cohesive Energy
Electronic Energy

Effect of Strain on Electronic Property



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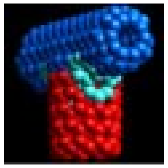
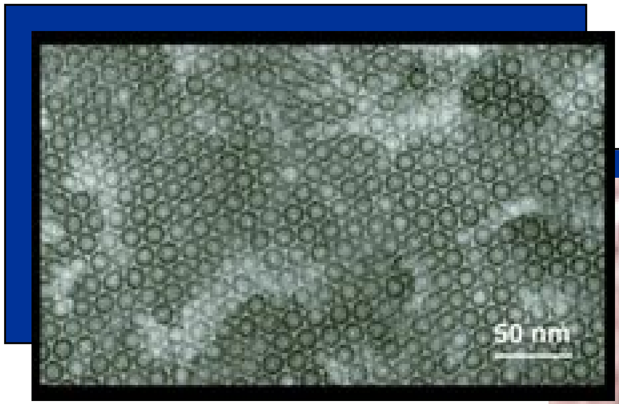
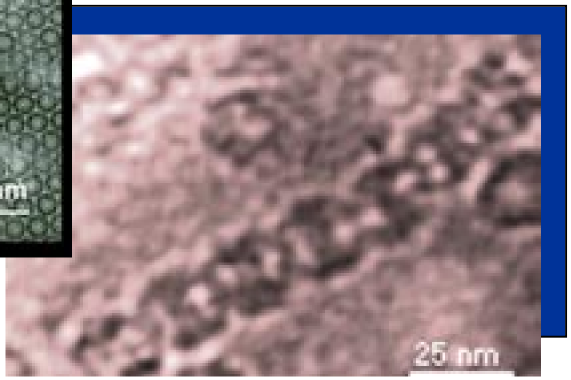
Protein Nanotubes

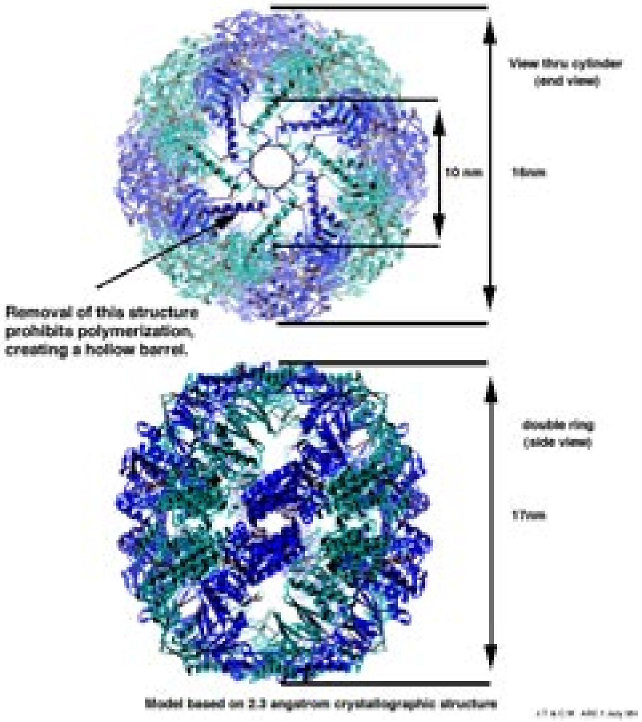


- Heat shock protein (HSP 60) in organisms living at high temperatures ("extremophiles") is of interest in astrobiology

- HSP 60 can be purified from cells as a double-ring structure consisting of 16-18 subunits. The double rings can be induced to self-assemble into nanotubes.







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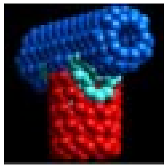

Summary

- Carbon nanotube has tremendous promise for future nanoelectronics, sensors/metrology, and structural application

- Progress in growth, characterization, and application exploration has been rapid. But a long way to go…

- Challenges/opportunities
  - Novel growth techniques, Large scale production
  - Control of properties, mechanisms
  - Characterization (electrical, mechanical…)
  - Application development
  - System level concepts